Design and testing of lifting system for a offsite volumetric housing prototype

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ABSTRACT: Offsite volumetric modular construction is getting considerable attention within the construction industry, especially in relation to the housing market. The study reported in this paper focuses on the design and testing of a lifting system for an offsite modular prototype made with light gauge steel members. The motivation of the research starts from the need to improve the design for lifting light gauge steel frames in modular construction. As time is critical in modular construction, the lifting method should be reliable and provide easy setup in the factory as well as onsite.

A desk study was carried out to outline the most practical solutions, then the module lifting locations were assessed to minimize deflection of the frame during lifting. The stability of the units and the local failure of the member were both considered. The lifting bracket was then designed with guidance from the European Standard EN 1993-1-2:2005. However, as the design of the lifting bracket is unique a set of experimental tests were carried out in the Heavy Structures Lab of Queen's University Belfast. The specimens, made connecting steel studs to connection brackets, were tested in tension in a Zwick Roell universal machine to replicate the modular house lifting conditions. The specimens were tested up to failure.

The testing showed the flaws of some of the designs and allowed to evaluate the tensile capacity of the lifting system. The modular house modules were manufactured in December 2017. The modular units were successfully lifted and connected to each other to form a three-bedrooms offsite volumetric house.

KEY WORDS: CERI 2018; modular; housing; lifting system; offsite modular systems.

1. INTRODUCTION

Modular construction has been established in the UK industry as an alternative form of construction for several decades. It developed from portable buildings, such as cabin and anti-vandal units, to large scale projects for schools, hospitals, offices and high-rise buildings. This development is driven by quantifiable economic benefits and sustainability as shown by the Value and Benefits Assessment of Modular Construction report by SCI, 2000, see Table 1.

Basic construction cost	£800/m²
Room rate per week (based on 70% occupancy)	£5/m²
Time saving in construction	20 weeks
Financial benefit	£100/m²
Loss of room bookings due to disruption (based on 20% loss)	£1.5/m²
Conventional construction period	45 weeks
Equivalent saving	£70/m²
Total saving	**£170/m²**
Percentage of construction cost	22%

Table 1 Savings due to modular construction [1].

The sustainability of modular construction method comes from the material savings, due to in factory manufacturing, and low operational energy for the lift time of the building [2]. The result shows that the average weight of material used is 148 kg/m^2 (main structural components) compared to 982 kg/m^2 to a typical construction in Sweden. The actual operational energy usage for the Open house buildings is 120 kWh/m^2, including space heating, hot water and lighting, equal to 6 MWh/m^2 for 50 years – 25% less than reference building [2]. In addition, the study estimates that the number of journeys required for project delivery can be 30% less compared to site based construction, leading to less CO2 due to transportation and city pollution.

The aesthetics of modular building has been changed dramatically over the past twenty years, with a greater emphasis on the architectural design. Murray Grove in Hackney, constructed in 1999, is a successful example. This 5-storey building comprises 80 modules in an L-shaped plan form, as seen in Figure 1. This residential building was designed for Peabody Trust, a social housing provider [2]. It is the only affordable housing scheme awarded the Millennium Product status by the Design Council [3].

The market demand for modular construction is said to be on the rise [5] especially in the housing market where modular construction is seen as a solution for housing shortage [6] Pinsent Masons published an overview of the housing market in February 2017 showings that in 2015, 142,890 homes were built, way below the target of 250,000; and 67% of 230 house-builders [5] by the Build Show said that off-site construction will be the key solution with the short construction time.

Figure 1 Murray Grove building [4].

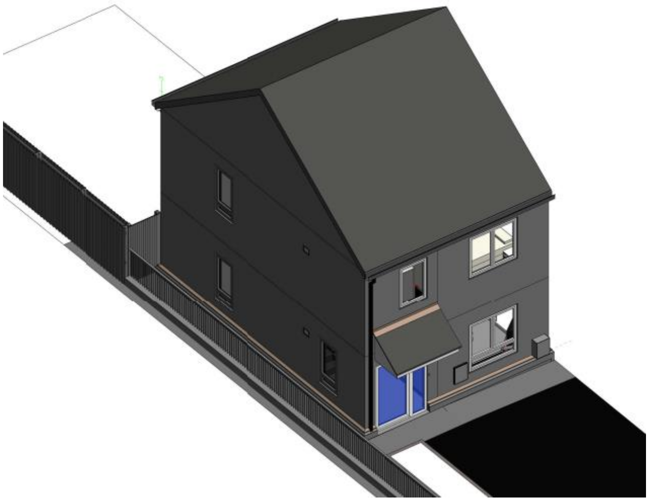


Figure 2 McAvoy prototype house 3D model (certified BIM LV2).

There are several companies investing in large modular housing factory. Laing O'Rourke are investing £104m in an offsite manufacturing facility in Worksop and L&G announced plans for a £55m, 550,000 sq ft offsite factory in Leeds and plans to invest a further £500m. However, despite the growth in manufacturing capability, the market demand for modular housing will still not be met. Laing O'Rourke's capacity is 10,000 new home per year and L&G is predicted to have 3,000 per year which is a small part of the target to fill the gap of housing crisis. In addition, the industry of modular housing is facing an economic and technical challenge, for example, Laing O'Rourke suffered a £53.1m net loss in European operations in 2016, largely because of technical difficulties in off-site building construction, associated with scaling up production volumes [7]. The government is encouraging modular housing, both the Central Government (via the DCLG) and the Greater London Authority (GLA) have been visiting various modular sites and the housing minister Gavin Barwell revealed that a £3bn Home Building Fund has been approved to support innovation in the industry [7].

2. MCAVOY LIGHT GAUGE STEEL HOUSE PROTOTYPE

In response to the housing crisis in the UK [6] in 2017 McAvoy Group started a prototype house project to develop an economy, high quality and fast construction method for single-family houses. The prototype design is a 3-bedroom, 5-people house. The structural frame of the house, made of light gauge steel members, is constructed using four modular units, two for ground floor and two for first floor, and timber roof, see Figure 3. Units size are 3x2.5x9 m for units 1 and 3 and 3.6x2.5x9 m for units 2 and 4, see Figure 4.

The lifting system for the modules was among the technical challenges of the project. In this paper the design of the lifting connections and experimental tests carried out to assess the possible solutions are reported.

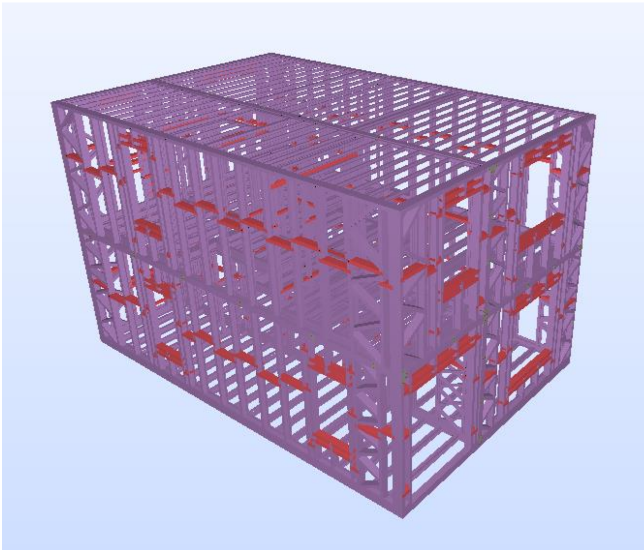


Figure 3 Light gauge steel frame – McAvoy.

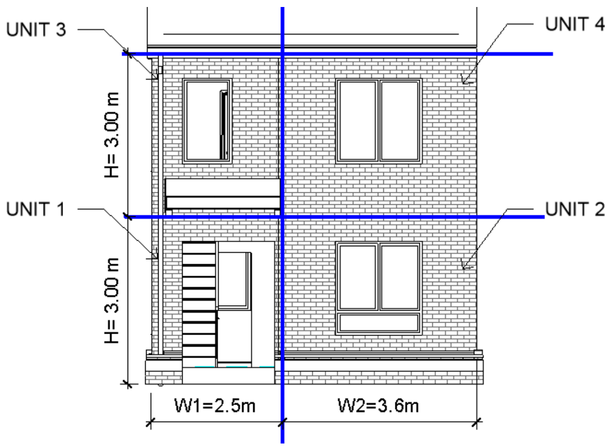


Figure 4 Elevation of modular house prototype.

3. LIFTING SOLUTIONS

As the modules need to be transported to the construction/assembly site, different lifting solutions were considered and divided into two main groups: lifting from the bottom and lifting from the top of the units. Units can be lifted from the bottom using straps connected to a rectangular lifting frame which is connected to the crane. The straps can either run underneath the module, or be connected to lifting points on the ground beams as shown in Figure 5. However, it is difficult to remove the lifting equipment once the units are placed on site. Lifting points can also be placed directly on roof beams as in Figure 6. In this case, however the roof beams need to be overdesigned making the solution less cost effective.

Figure 5 Lifting points on ground beams [8].

Figure 6 Light gauge unit with lifting point on roof beams [9].

3.1 Prototype lifting designs

For the McAvoy prototype project an in-house solution was designed and tested. A vertical load of 17.5 kN was considered per each lifting point.

The solution consisted of studs running vertically along the height of the modular unit and connected to both roof and ground beams on six lifting points (three per side) through brackets and M16 lifting eyes. The studs selected were channel sections, 150x65x1.2 mm for external walls (for insulating purpose) and 64x42x1.2 mm for internal walls.

Two designs of the brackets were considered: in design 1 (D1) a bracket was fitted inside the stud, in design 2 (D2) the bracket was connected to the external stud surface, see Figure 7.

D1 brackets were made with a folded 4 mm steel plate and a welded plate at one end ("top plate" in Figure 7). The end plate had a ø40mm hole and a pre-welded nut underneath for the M16 lifting eye to be screwed on. The bracket was connected to the stud through twelve 4.8 mm self-tapping screws, four per each side, see Figure 8. The roof beam was inserted between the bracket and lifting eye.

Bracket D2 consisted of a folded steel plate and triangular stiffeners, see Figure 8(b). The steel section was bolted to the stud with 7 screws at 35 mm spacing (for the 64 mm studs) and 12 screws at 35 mm spacing (for the 150 mm studs). As for the previous design the lifting eye nut was pre-welded underneath the top plate.

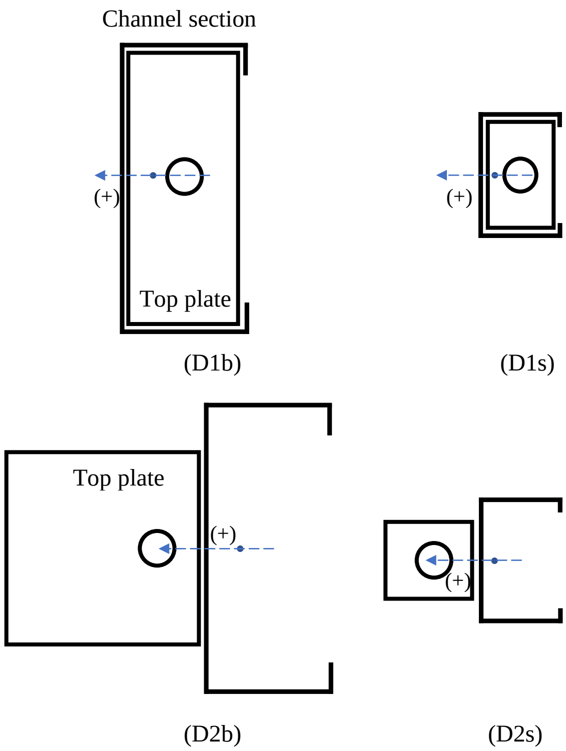


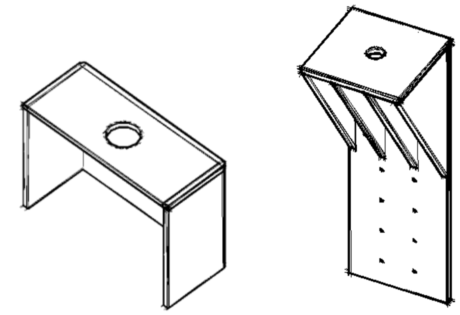
Figure 7 Bracket-stud section for design D1 and D2 and two stud-bracket connections "b" and "s".

Two different lifting eye types were used for testing. In test series S1, the lifting eye had the handle beside the connecting bolt and could rotate about it, see Figure 9(a). Therefore, the axial force position during the lifting could assume different values of eccentricity with respect to the stud centroid. The eccentricity of the handle with respect to the central bolt was ± 25 mm. In test series S2, the lifting eye had the handle above the bolt in a symmetric position, see Figure 9(b).

Table 1 reports the specimen main geometrical characteristics. The specimen name consists of the design type

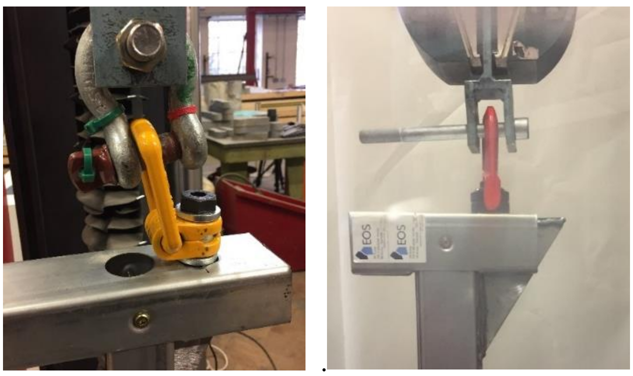
(D1 or D2), stud size (“s” for 64 mm and “b” for 150 mm), test series (S1 or S2) and specimen number following the test series.

D2b_S13_6 had fewer screws (six only) than the other specimens of the same type. In the table is also reported the lifting eye hole eccentricity with respect to the channel centroid for each bracket design (D1, D2), test series (S1, S2) and stud-bracket size. During the tests the position of the lifting eye handle was always setup as to minimise the total eccentricity of the lifting force with respect to the channel.



(D1) (D2)

Figure 8 Bracket designs D1 and D2.



(a) (b)

Figure 9 Lifting eye; a) test series S1; b) test series S2.

4. EXPERIMENTAL TESTS

To assess the structural capacity of the lifting systems, specimens of the different stud/bracket connections were manufactured in McAvoy and tested in the Heavy Structures Lab of Queen’s University Belfast. Two sets of tests were carried out, one with asymmetric lifting eyes (S1) and one with symmetric lifting eyes (S2). Only one specimen per size was tested for design D1, while three S1 and two S2 specimens were tested for design D2 per each stud size.

The tests were carried out using a Zwick Roell 100 kN universal machine in displacement control mode. A loading rate of 5 mm/min was applied. The test setup is shown in Figure 10.

To simulate the crane hook connection, the lifting eye was supported by a horizontal bolt, as shown in Figure 9. The designed brackets were fixed at both ends of the studs and the bottom bracket was fixed to the base plate of the machine with an M16 bolt.

Table 1 Specimen geometry

Stud	Top plate	Specimen	Lift eye ecc	handle ecc
(mm)	(mm)		(mm)	(mm)
64x42x1.2	61x39	D1s_S11	-7.3	18.8
	40x45	D2s_S11	34.7	-18.8
		D2s_S12	34.7	-18.8
		D2s_S13	34.7	-18.8
		D2s_S21	34.7	0.0
		D2s_S22	34.7	0.0
150x65x1.2	141x57	D1b_S11	-13.1	18.8
	100x100	D2b_S11	37.9	-18.8
		D2b_S12	37.9	-18.8
		D2b_S13_6	37.9	-18.8
		D2b_S21	37.9	0.0
		D2b_S22	37.9	0.0

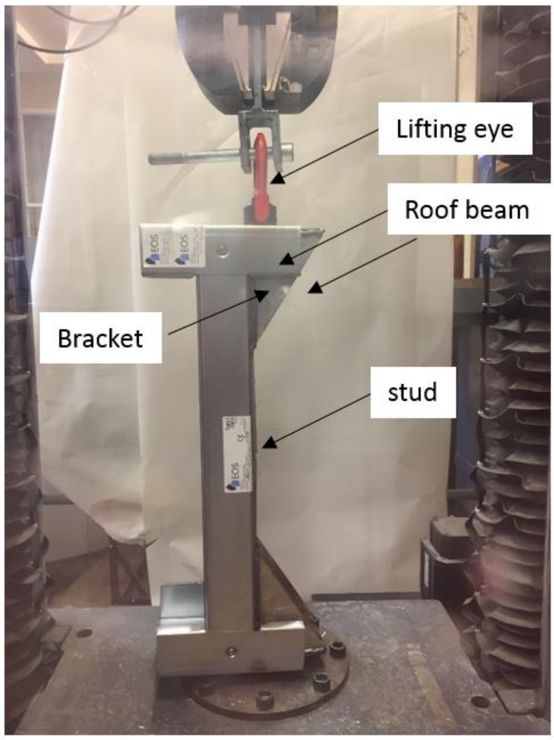


Figure 10 Test set-up.

5. RESULTS

5.1 Force displacement curves

The force-displacement curves for the 64 mm stud/bracket specimens are plotted in Figure 11. Peak load and corresponding displacement values are reported in Table 2 together with the ultimate displacement and initial slope (calculated between 5 kN and 10 kN).

The average peak load of the six small stud-bracket specimens (64 mm) was 37.8 kN with a small coefficient of variation

(10%). On the contrary the peak displacement spread from 7.4 mm to 23.4 mm with an average of 14.2 mm and coefficient of variation equal to 0.45 for the different bracket and lifting eye types. Specimen D1s_S1 showed a bilinear trend with a change of slope at about 12 kN. Several load drops took place after the peak load was reached. A similar bilinear trend was shown by one of the three D2s_S1 specimens while the other two experienced a less marked change of stiffness. For the D2s_S1 specimens the failure was also less ductile compared to the D1s_S1 specimens.

Specimens with type 2 lifting eye mainteined an almost linear behaviour up to the load peak with a sudden loss of bearing capacity afterwards. These specimens also showed the highest initial stiffness (between 5.42 and 5.47 kN/m).

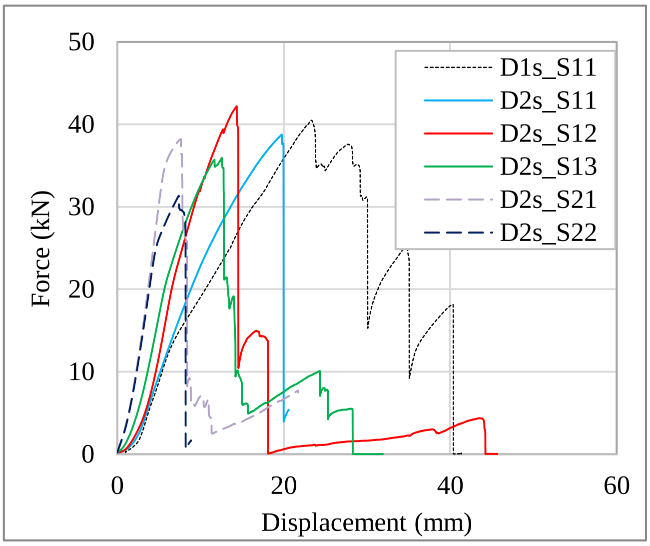


Figure 11 Tensile tests of 64 mm bracket-stud specimens.

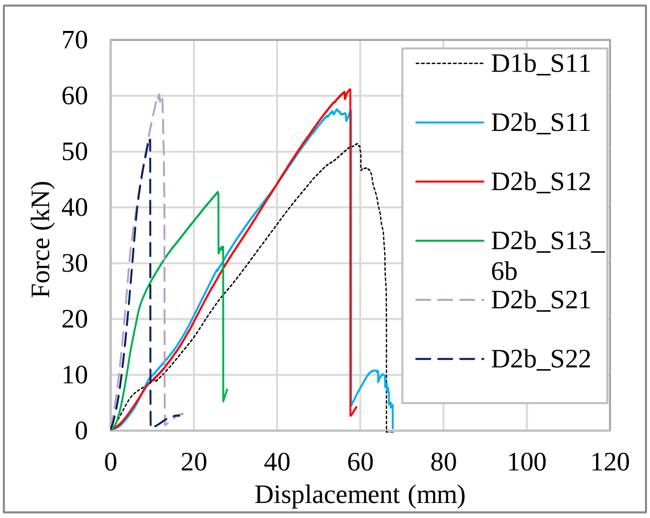


Figure 12 Tensile tests of 150 mm bracket-stud specimens.

The force-displacement curves for the 150 mm stud/bracket specimens are plotted in Figure 12. Also in this case there was a marked difference between S1 specimens and S2 specimens. Peak load values fell in the interval 51.4 and 61.2 kN for five specimens out of six. Specimen D2b_S13_6 had a much lower peak load but a stiffness closer to D2b_S2 specimens.

Except for this specimen the two sets of curves had close peak displacement values, about 57.1 mm for S1 series and about 10.6 mm for series S2. Series S1 showed an early change of stiffness at about 8 kN while S2 had an almosty linear trend up to failure. All the 150 mm specimens had a less ductile failure compared to the small size stud/brackets.

Table 2 Results

Specimen Name	**Peak force (kN)**	**Peak displ (mm)**	**Init stiffness (kN/m)**	**Ult dislp (mm)**
D1s_S11	40.5	23.4	3.00	41.3
D2s_S11	38.8	19.8	3.01	20.6
D2s_S12	42.2	14.3	3.84	45.6
D2s_S13	35.9	12.6	4.04	31.9
D2s_S21	38.2	7.6	5.47	21.7
D2s_S22	31.3	7.4	5.42	8.9
Average	**37.8**	**14.2**	**4.13**	**28.3**
CoV	**0.10**	**0.45**	**0.27**	**0.49**
D1b_S11	51.4	59.3	1.20	68.3
D2b_S11	57.6	54.5	2.91	67.8
D2b_S12	61.2	57.6	2.46	59.0
D2b_S13_6	42.8	25.8	4.14	28.0
D2b_S21	60.3	11.6	5.76	17.3
D2b_S22	52.1	9.5	4.93	16.4
Average	**54.2**	**36.4**	**3.57**	**42.8**
CoV	**0.13**	**0.64**	**0.47**	**0.58**

1.1 Failure modes

The D1 specimens failed due to the braking of welds of the bracket plate as shown in Figure 13 for for D1s_S11. Moreover, the beam section interposed between the top plate and lifting eye was distorted and bent due to the eccentricity of the lifting eye handle.

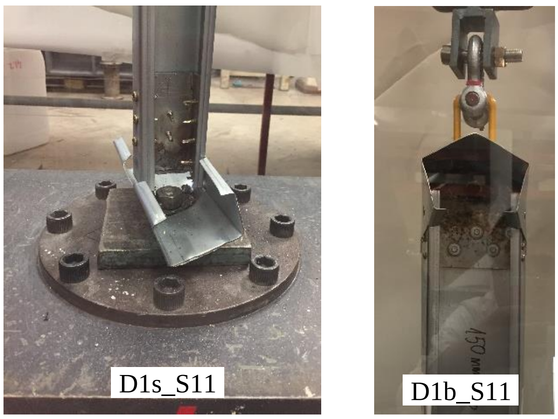


Figure 13 D1 specimens at failure.

D2 specimens for both series 1 and 2 experienced a sudden failure due to the unsufficient connection of the bracket section to the stud. At peak load all the fixing screws started to come off at nearly the same time. D2 specimens with the symmetric lifting eye retained experienced less bending and distorsion of brackets, stud and connected beams. Photos of the different failure types are shown in Figure 13 - Figure 15.

Figure 14 D2 specimen (64 mm stud) at failure.

Figure 15 D2 specimen (150 mm stud) at failure.

6. CONCLUSIONS

A set of experimental tests for assessing on-site lifting conditions of a prototype modular house are reported in this paper. Two bracket-stud connection types were designed and tested, each one for two different stud sizes and using different lifting eye types.

All the specimens had a capacity at least double than the design load (17 kN). While the two designs showed very different deformation patterns, they had similar strength values for both the small and the large stud-bracket connections (average values 37.8 kN and 54.2 kN for the 64 mm and 150 mm studs respectively).

The choice of the commercial lifting eye used affected significantly the deformed shape of both the stud-bracket connections and interposed beam. The asymmetric lifting eye used for test series 1 caused the distorsion of the light steel elements connected for values of the load lower than the design load.

Design D2 specimens with lifting eye type 2 showed the highest stiffness. This bracket-stud connection was selected and implemented for the McAvoy Modular House Project, see Figure 16.

Figure 16 D2s connection on the light steel gauge module.

REFERENCES

[1] Rogan, A. L., R. M. Lawson, and N. Bates-Brkljac. "Value and benefits assessment of modular construction." *Steel Construction Institute, Ascot, UK* (2000).

[2] Lawson, M., Ogden, R., & Goodier, C. (2014). *Design in modular construction*. CRC Press.

[3] 2015 Cartwright Pickard Architects. Retrieved from: http://www.cartwrightpickard.com/projects/offsite/murray-grove/

[4] Tarquin Binary (2006), distributed under a CC-BY 2.0 license.

[5] Middleton, C. (2017). "Demand for offsite manufacturing is on the Rise". Retrieved from http://www.bqlive.co.uk/construction/2017/12/11/news/demand-for-offsite-manufacturing-is-on-the-rise-29414/

[6] Gardiner, J. (2017). "Can prefab homes solve UK's housing crisis?" Retrieved from https://www.theguardian.com/sustainable-business/2017/jan/26/prefab-homes-uk-housing-crisis-modular-offsite-construction-manchester-liverpool-energy-efficiency

[7] Pinsent Masons (2017). "Modular Construction in UK", *An Overview of the Market, the Players and the Issues Pinsent Masons Research Housing*. Retrieved from http://constructingexcellence.org.uk/wp-content/uploads/2017/02/graham-robinson-pinsent-masons-14022017.pdf

[8] ParkWood Modular Buildings. Terrace Home Construction / Installation. Retrieved from https://www.parkwoodhomes.com.au/gallery/

[9] Lawson, M. (2012). ED014 Light steel framing and modular construction. *The Steel Construction Institute.*